NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

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EXPERIMENTAL STUDIES OF THE KNOCK-LIMITED BLENDING CHARACTERISTICS OF AVIATION FUELS

III - AROMATICS AND CYCLOPARAFFINS

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SUMMARY

The knock-limited power at various blend compositions for several aromatics and cycloparaffins individually blended with paraffinic base stocks, as determined in an air-cooled aircraft-engine cylinder at fuel-air ratios of 0.07 and 0.10 is presented. An analysis of the data leads to the conclusion that the extended reciprocal blending relation suggested in a previous NACA report is not generally applicable to such nonparaffinic components, but might possibly be useful as an approximation over a limited range of composition for aromatic blends.

INTRODUCTION

The relation between knock-limited power and blend composition has been the subject of several NACA investigations. The reciprocal blending relation proposed in reference 1 for supercharged knock data was found in reference 2 to be applicable at a fuel-air ratio of 0.10 to several paraffinic blends tested in an aircraft cylinder. A later investigation on the same cylinder showed that the reciprocal blending relation was generally followed at both lean and rich mixtures when the temperature of the combustion-chamber wall near the knocking zone was held constant; this conclusion applied at the two operating conditions investigated, for blends of various paraffinic fuels (reference 3) and also for blends of two paraffinic fuels each having the same concentration of aromatics (unpublished data).

Reference 2 also reported that several blends of nonparaffinic fuels with paraffinic fuels did not follow the reciprocal relation and suggested the following extended form of the reciprocal relation for such blends:

$$\frac{N_1\beta_1 + N_2\beta_2 + \cdots}{P_b} = \frac{N_1\beta_1}{P_1} + \frac{N_2\beta_2}{P_2} + \cdots$$

where

N_1, N_2, ... weight percentages of components 1, 2, ..., respectively

β_1, β_2, ... blending constants for components 1, 2, ..., respectively

P_b, P_1, P_2, ... knock-limited indicated mean effective pressures of blend and of components 1, 2, ..., respectively

Hereinafter, subscript 1 is used to refer to nonparaffinic components and subscript 2 to paraffinic components.

The simple reciprocal relation of reference 1 may be considered to be a special case of the foregoing extended reciprocal relation in which the β's are all the same and so cancel out. The value of β for paraffinic S reference fuel may be taken as 1.0, and if all paraffins followed the simple reciprocal relation then β for all paraffins would be 1.0.

The purposes of this investigation, which was conducted at the NACA Cleveland laboratory, were to determine the knock-limited blending characteristics of several aromatics and cycloparaffins individually blended with paraffinic base stocks, and to test the applicability of the extended reciprocal blending relation for such nonparaffinic components.

FUELS

The following aromatics and cycloparaffins were used as one component of the blends:

Aromatics:
- Benzene
- Toluene
- Xylene
- Cumene

Cycloparaffins:
- Cyclopentane
- Methylcyclopentane
- Cyclohexane
- Methylcyclohexane
- Ethylcyclohexane

These nonparaffins were individually blended in various proportions with each of the following three paraffinic base stocks:

- Alkylate
- Virgin base
- A blend of 50 percent S-4 reference fuel with 50 percent M-4 reference fuel. This blended base stock is hereinafter designated 50/50 S/M

The xylene contained about 15-percent o-xylene, 47-percent m-xylene, 24-percent p-xylene, 11-percent ethylbenzene, and 3 percent other compounds, according to ultraviolet spectrophotometric analysis by this laboratory. It was estimated from the refractive indices and other inspection data that the impurities amounted to 8 percent in the cyclopentane and 5 percent or less in the other nonparaffins. The combined aromatic and olefinic content (mostly aromatic) of the base stocks was as follows: alkylate, less than 1 percent; virgin base, 10 percent; 50/50 S/M, 5 percent.

All fuels contained 4 ml tetraethyl lead per U.S. gallon. Blend compositions throughout this paper are reported in percentage by weight.

APPARATUS AND OPERATING CONDITIONS

The apparatus, which consisted of an R-2800 cylinder mounted on a CUE crankcase and associated equipment, was practically the same as described in detail in reference 2 except for the following two alterations: In regulating the cooling-air flow, a thermocouple embedded in the cylinder head about 1/16 inch from the combustion-chamber wall near the knocking zone was used as the reference point instead of the rear-spark-plug-boss thermocouple. The knocking zone was assumed to coincide with the exhaust end zone, which was about 25° (due to swirl) from the exhaust valve toward the rear of the cylinder. Also, an altitude exhaust system was installed and the exhaust back pressure was maintained constant at 15 inches of mercury absolute instead of at atmospheric pressure.

These alterations were made because a previous unpublished investigation on this engine setup indicated that better reproducibility might thereby result. It had also been found (reference 3) that the knock data at lean mixtures for paraffinic fuel blends gave better agreement with the reciprocal blending equation when the cylinder-head temperature near the knocking zone was held constant.

The engine operating conditions were as follows:

Compression ratio	7.3
Spark advance, both plugs, deg B.T.C.	20
Engine speed, rpm	2250
Inlet-mixture temperature, °F	240
Exhaust back pressure, in. Hg abs.	15
Cylinder-head temperature at exhaust end zone, °F	400
Rear-spark-plug-boss temperature, °F	426-469
Cooling-air temperature, °F	90
Oil pressure, lb/sq in.	60
Oil-in temperature, °F	185

These engine conditions were chosen to give good reproducibility and sufficient severity to permit knock ratings with large proportions of the high-performance nonparaffin components. The investigation was made over a 3-month period during which two cylinder overhauls were necessary.

PROCEDURE

Blending-response runs were made at fuel-air ratios of 0.07 and 0.10. The blend composition was adjusted by proportioning the flows in the two independent fuel systems, one containing the nonparaffin and the other containing one of the base fuels. In most cases, three blend compositions were tested besides the straight base fuel and the straight nonparaffin, making a total of at least four or five data points in a series.

Blends of a given nonparaffin with the three base stocks at the same fuel-air ratio were tested on one day or on two consecutive working days. In an effort to get better reliability, the data points were repeated and several procedures were used. In some cases, after running the four or five blend points in a series the runs were immediately repeated by another operator. In other cases, the three series of points from one nonparaffin with the three bases at one fuel-air ratio were run one day and then repeated the next day by another operator. And in still other cases, the checking was done after a longer time had elapsed.

Inasmuch as it was impossible to keep the fuel-air ratio exactly at 0.07 and 0.10 in all the blending-response runs, approximate corrections were applied to the data in accordance with the trends of mixture-response curves at those fuel-air ratios. The corrections were very small in general because the fuel-air ratio was maintained within ±0.001 fuel-air ratio of 0.07 and 0.10 in all except 7 percent of the runs.

RESULTS AND DISCUSSION

Base-fuel mixture response. - Curves showing the knock-limited indicated mean effective pressures and indicated specific fuel consumptions plotted against fuel-air ratio for the three base fuels used in this investigation are given in figure 1; for comparison, a curve for S-4 reference fuel is also included in this figure. These curves represent approximately the average performance over the entire test period. The indicated-specific-fuel-consumption curves for these four fuels were practically the same so only one average curve is shown.

Base-fuel reproducibility. - Complete mixture-response data for each base fuel were taken about five times during the program, but tests at fuel-air ratios of 0.07 and 0.10 were repeated more than 30 times. The following table shows the reproducibility obtained at these two fuel-air ratios:

Fuel-air ratio	Base fuel (a)	Knock-limited imep (lb/sq in.)			imep deviation (percent)	
		Maximum	Minimum	Average	Maximum	Average
0.07	Alkylate	169	145	158	8.2	3.6
	Virgin base	123	102	111	10.8	4.0
	50/50 S/M	97	88	93	5.4	2.1
0.10	Alkylate	216	197	207	4.8	1.9
	Virgin base	159	139	149	6.7	2.4
	50/50 S/M	112	106	109	2.8	1.0

[a]All fuels contain 4 ml TEL per gallon.

Some of the series of blending runs contained only one rating of the base fuel; whereas in other series the base fuel was tested at the beginning and end of the series and sometimes in the middle. The two or three values so obtained were first averaged, and then the average of all series determined. The maximum and minimum values given in the table are, however, taken from all the individual ratings.

The average deviation in indicated specific fuel consumption for all the base-fuel runs at both fuel-air ratios was 0.6 percent, and the maximum deviation was 2.7 percent.

Base-fuel blending characteristics. - The blending characteristics of the base fuels blended with each other are shown in figure 2. The ordinate scale is an inverted reciprocal scale so that a straight line is obtained if the blend follows the simple reciprocal relation (reference 2). The four pairs of fuels shown in this figure gave straight lines at both fuel-air ratios, within the experimental error. The point for 100-percent S-4 reference fuel in blends of S-4 reference fuel with 50/50 S/M at a fuel-air ratio of 0.10, which seems to be low, is still considered to be within the experimental error for that power level. Tailed points are shown for the preceding and succeeding ratings of S-4 reference fuel.

Blends of virgin base with 50/50 S/M were not tested at a fuel-air ratio of 0.07 but it may be assumed that the reciprocal relation would probably apply inasmuch as it applies to blends of alkylate with each of these two bases.

Aromatic mixture response. - It was impossible to obtain knock data at fuel-air ratios richer than 0.068 for the straight aromatics except cumene, because of engine limitations. A partial mixture-response curve obtained with straight cumene showed the minimum indicated mean effective pressure to be 130 pounds per square inch at a fuel-air ratio of 0.066, with a rise to 145 at 0.070 and to 190 at 0.076. In addition to the high knock-limited powers, another difficulty encountered in attempting to test the straight aromatics and even some of the blends containing very large proportions of aromatics (except cumene at lean mixtures) was the irregular character of the knock.

Aromatic blending response and reproducibility. - Figures 3 and 4 present the blending characteristics of the aromatics individually blended with each of the three base fuels at fuel-air ratios of 0.07 and 0.10. The widest spread of data was obtained with the benzene-alkylate blends (fig. 3), which include three series of runs that serve as a check on the reproducibility estimated for the aromatic blends.

The reproducibility with aromatic blends over the entire 3-month period would probably be worse than that for the paraffinic base fuels, but the aromatic runs were actually made over a much shorter period of time and the interest here is primarily in the shape of the curves relative to each other. As a rough estimation, the base-fuel reproducibility values were therefore applied also to the aromatic blends

and it was assumed that the average imep deviation of any single determination was about 2 percent at a fuel-air ratio of 0.10 and 4 percent at 0.07; and the maximum deviation was assumed to be about 5 percent at 0.10 and 10 percent at 0.07. These precision values are consistent with the computed deviations from the faired curves for the benzene-alkylate data, although the data are insufficient for a reliable analysis.

The knock-limited indicated mean effective pressure ratios of blend relative to base fuel for all the nonparaffins investigated are shown in table I. The aromatic-blend values in this table were derived from the blending-response curves faired through all the experimental data in figures 3 and 4. The values on the faired curves of these figures are equivalent to averages of several determinations and therefore the precision of such values should be considerably better than that given for a single determination, perhaps about twice as accurate, except near the high-power end of the curves.

Testing blending relation for aromatics. - The following method was used in determining the applicability of the extended reciprocal blending relation to blends of a nonparaffin with paraffin base stocks: A method of plotting is used whereby one straight line can be drawn through all the data for a given nonparaffin blended in varying proportions with various base stocks at constant fuel-air ratio; the position of this straight line determines the unknown β_1, and also P_1 if it cannot be experimentally determined.

The extended reciprocal equation for two components is the equation of an equilateral hyperbola if P_b and N_1 are considered to be the variables. This equation can, however, be rearranged to the intercept form of a straight line as follows:

$$\frac{P_b}{P_1} + \frac{\left(\frac{100 - N_1}{N_1}\right)\left(\frac{P_b - P_2}{P_2}\right)}{\beta_1/\beta_2} = 1$$

Then if the data are plotted with P_b as the abscissa and $\left(\frac{100 - N_1}{N_1}\right)\left(\frac{P_b - P_2}{P_2}\right)$ as the ordinate, a straight line would result if the extended reciprocal relation is applicable, with the abscissa intercept equal to P_1 and the ordinate intercept

equal to β_1/β_2. It has been shown that the paraffin base stocks used under the conditions of this investigation followed the simple reciprocal relation; hence, β_2 may be taken as 1.0. Sample plots of this type are shown in figure 5; data points are from the faired curves in figure 3 for benzene. The criterion used in choosing the best straight line was the difference between the values of P_b determined by this line and the experimental values; a greater weight was given to the closeness of fit at the lower aromatic concentrations.

As a result of such analyses applied to all the aromatic blends, the following values of β_1 and P_1 were chosen:

Aromatic	Fuel-air ratio, 0.07		Fuel-air ratio, 0.10	
	β_1	P_1 (lb/sq in.)	β_1	P_1 (lb/sq in.)
Benzene	0.06	-100	0.5	400
Toluene	.5	300	.5	∞
Xylene	.3	240	1.0	400
Cumene	1.0	140	1.0	350

The negative value of P_1 given in this table means that if the reciprocal relation were applicable over the entire range of composition, fuels containing high concentrations of such a compound would be completely knock-free; in this case for example, benzene-alkylate blends containing 91.3 percent or more benzene would be knock-free (mathematically, P_b becomes infinite when

$$N_1 = \frac{100 \frac{\beta_2}{P_2}}{\frac{\beta_2}{P_2} - \frac{\beta_1}{P_1}}$$

The dashed curves in figures 3 and 4 show the blending-relation indicated mean effective pressures corresponding to the values of β_1 and P_1 given in the preceding table. The differences between the experimental indicated mean effective pressures and those predicted by the blending relation, expecially toward the high-power end of the curves, are considerably greater than the estimated error. It is therefore concluded that the extended reciprocal blending relation cannot be generally applied over the entire range of composition.

The possibility remains, however, that the extended blending relation may be of some use as an approximation over a limited range; for blends containing less than 25 percent aromatic hydrocarbons, the maximum difference between the predicted indicated mean effective pressures and the faired-curve values was 5 percent. When blends of aromatics with various base fuels of widely differing antiknock quality are considered, it is believed that such a method of estimating ratings would be more accurate than any method based on linear extrapolation of blend ratings to the rating for the straight compound. Whether the increase in accuracy would be worth the additional complication of a blending constant would depend on several factors, such as the range of base-fuel antiknock quality and the engine operating conditions.

It was found that an equilateral hyperbola could be fitted to the blending data within the estimated error for each curve separately but the three hyperbolas for a given aromatic would not intercept the 100-percent line at the same point, as they should; that is, they require different values of P_1 and also of β_1. The fact that they require different values means that as the 100-percent aromatic composition is approached, the blending curves must deviate from the hyperbolic form.

Cycloparaffin mixture response. - The mixture-response data for the straight cycloparaffins are presented in figure 6. These mixture-response curves are not closely comparable on an absolute basis because they were determined at intervals of about 1 week apart (over a total period of 1 month). The general shapes of the indicated-mean-effective-pressure curves seem to divide them, however, into two groups, cyclopentane and cyclohexane having similar curves, and the three alkyl cycloparaffins forming a second group of similar curves. The indicated specific fuel consumptions for the five cycloparaffins are practically all the same, and they are also practically the same as for the paraffinic base fuels (fig. 1).

Cycloparaffin reproducibility. - During the course of the investigation, from four to eight knock tests were made on each straight cycloparaffin at fuel-air ratios of 0.07 and 0.10. An analysis of these data indicated that the cycloparaffin reproducibility was approximately the same as that estimated for the aromatic blends.

Cycloparaffin blending characteristics. - The blending response of the cycloparaffins individually blended with each of the three base fuels is shown in figures 7 and 8 and table I. It was not generally possible to apply the extended reciprocal blending relation

to these blends. A number of the blending curves exhibit the phenomenon of a blend that permits higher knock-limited performance than either component and this phenomenon cannot be expressed by the reciprocal blending equation.

An equation that could closely match such curves would have to contain several blending constants for each component, and the procedure of determining such constants would probably be impractical in view of the number of the tests required and the limited degree of precision attainable.

SUMMARY OF RESULTS

An investigation of the knock-limited blending characteristics of several aromatics and cycloparaffins individually blended with paraffinic base stocks in an air-cooled aircraft-engine cylinder gave the following results:

1. The knock-limited indicated mean effective pressures of the paraffinic base fuels followed the simple reciprocal blending relation under the operating conditions used.

2. The extended reciprocal blending relation could not be applied to all the aromatic-blend data within the extimated maximum error of 5 percent at a fuel-air ratio of 0.10 and 10 percent at a fuel-air ratio of 0.07; it was possible to use the extended reciprocal relation as an approximation over a limited range of composition, up to about 25 percent aromatics.

3. It was impossible to apply generally the extended reciprocal blending relation to the cycloparaffin blends, some of which gave higher knock-limited power than either component in the blend.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, June 17, 1947.

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2. Sanders, Newell D., Hensley, Reece V., and Breitwieser, Roland: Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. I - Preliminary Tests in an Air-Cooled Cylinder. NACA ARR No. E4I28, 1944.

3. Wear, Jerrold D., and Sanders, Newell D.: Experimental Studies of the Knock-Limited Blending Characteristics of Aviation Fuels. II - Investigation of Leaded Paraffinic Fuels in an Air-Cooled Cylinder. NACA TN No. 1374, 1947.

TABLE I. - BLENDING CHARACTERISTICS OF AROMATICS AND CYCLOPARAFFINS IN AIRCRAFT-ENGINE CYLINDER

Base fuel plus nonparaffin	Knock-limited imep ratio of blend relative to base fuel[b]									
	Fuel-air ratio, 0.07					Fuel-air ratio, 0.10				
	Nonparaffin, weight percent					Nonparaffin, weight percent				
(a)	10	25	50	75	100	10	25	50	75	100
Alkylate plus										
Benzene	1.02	1.06	1.19	1.54	---	1.02	1.06	1.20	---	---
Toluene	1.02	1.06	1.13	1.45	---	1.06	1.18	---	---	---
Xylene	1.01	1.03	1.06	1.12	---	1.03	1.14	---	---	---
Cumene	.99	.96	.92	.89	0.85	1.04	1.13	---	---	---
Cyclopentane	1.01	1.02	.94	.86	.77	1.08	1.11	1.08	1.05	0.97
Methylcyclopentane	.96	.91	.84	.77	.71	1.05	1.07	.98	.90	.81
Cyclohexane	.94	.86	.74	.64	.54	1.04	1.06	.95	.84	.74
Methylcyclohexane	.96	.89	.77	.67	.59	.98	.95	.86	.75	.64
Ethylcyclohexane	.90	.78	.65	.53	.48	.92	.81	.67	.58	.51
Virgin base plus										
Benzene	1.01	1.04	1.13	1.52	---	1.03	1.09	1.28	---	---
Toluene	1.03	1.10	1.26	1.58	---	1.04	1.12	1.37	---	---
Xylene	1.01	1.03	1.09	1.28	---	1.05	1.13	1.37	---	---
Cumene	1.01	1.04	1.09	1.15	1.38	1.04	1.12	1.28	1.63	---
Cyclopentane	1.02	1.04	1.05	1.06	1.07	1.08	1.18	1.28	1.35	1.37
Methylcyclopentane	1.00	.99	.99	.98	.98	1.01	1.03	1.05	1.07	1.09
Cyclohexane	.97	.94	.88	.82	.76	1.02	1.03	1.04	1.03	1.02
Methylcyclohexane	.97	.94	.89	.85	.82	1.02	1.04	1.02	.97	.92
Ethylcyclohexane	.95	.90	.81	.73	.68	.97	.92	.85	.79	.74
50/50 S/M plus										
Benzene	1.01	1.03	1.16	1.60	---	1.04	1.11	1.34	2.24	---
Toluene	1.03	1.09	1.30	1.89	---	1.06	1.20	1.67	---	---
Xylene	1.02	1.08	1.24	1.55	---	1.07	1.25	1.76	---	---
Cumene	1.03	1.10	1.22	1.40	1.71	1.09	1.25	1.60	2.25	---
Cyclopentane	1.16	1.27	1.29	1.30	1.29	1.26	1.57	1.89	1.96	1.93
Methylcyclopentane	1.08	1.16	1.20	1.19	1.15	1.13	1.28	1.44	1.47	1.48
Cyclohexane	1.02	1.03	1.04	1.00	.90	1.16	1.33	1.45	1.44	1.41
Methylcyclohexane	1.03	1.07	1.09	1.05	.98	1.06	1.15	1.29	1.25	1.21
Ethylcyclohexane	.98	.95	.90	.84	.80	1.00	.99	.99	.98	.97

[a]All fuels contain 4 ml TEL per gallon.

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[b]Average knock-limited imep ratios for 50/50 S/M, virgin base, alkylate, and S-4 reference fuel respectively, relative to 50/50 S/M:
At a fuel-air ratio of 0.07; 1.00, 1.20, 1.70, 2.00.
At a fuel-air ratio of 0.10; 1.00, 1.37, 1.90, 2.19.

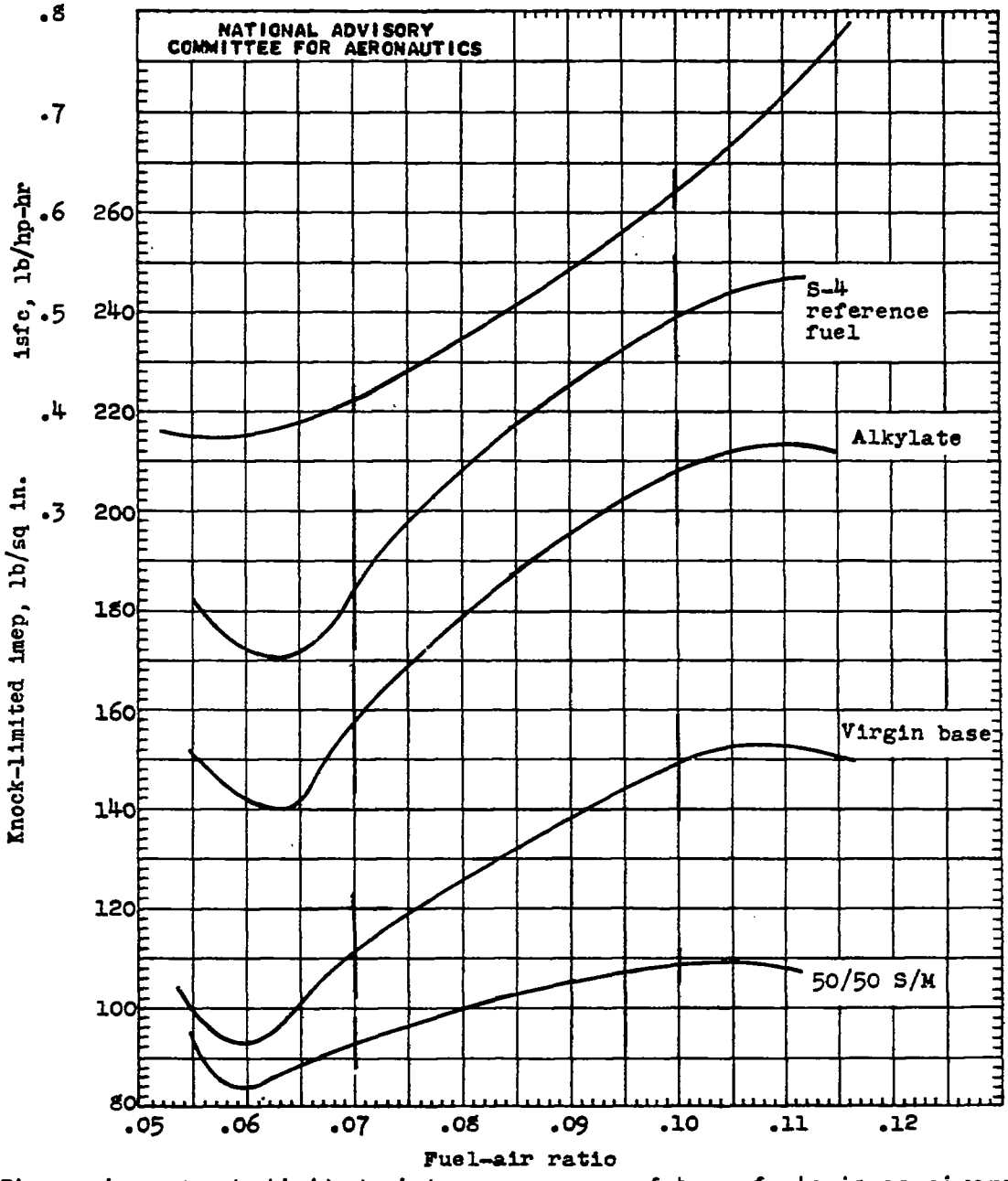

Figure 1. - Knock-limited mixture response of base fuels in an aircraft-engine cylinder. All fuels contain 4 ml TEL per gallon. These curves represent averages over the 3-month test period. The vertical lines show the spread obtained at fuel-air ratios of 0.07 and 0.10 during this period.

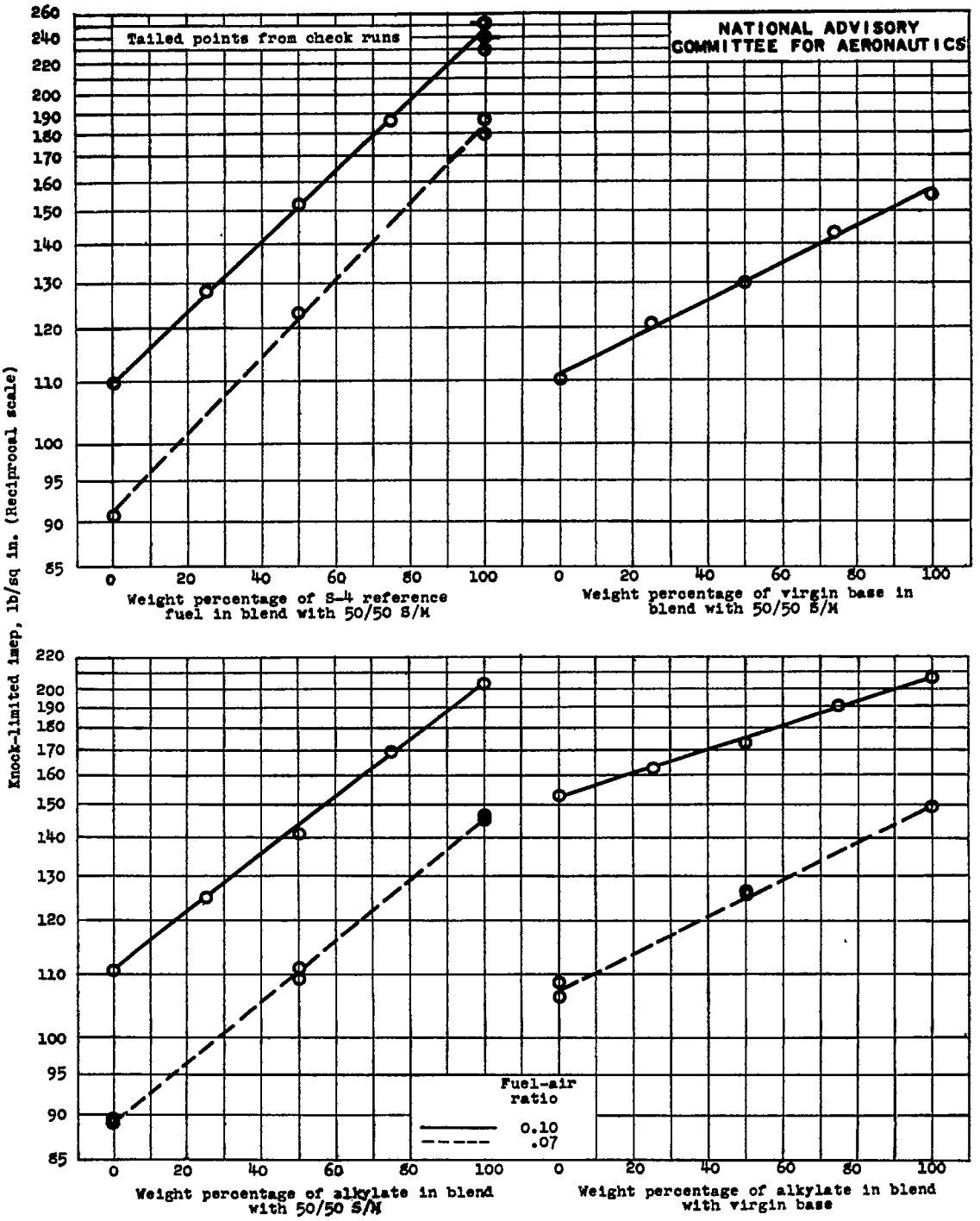

Figure 2. - Knock-limited blending characteristics of base fuels in an aircraft-engine cylinder. All fuels contain 4 ml TEL per gallon.

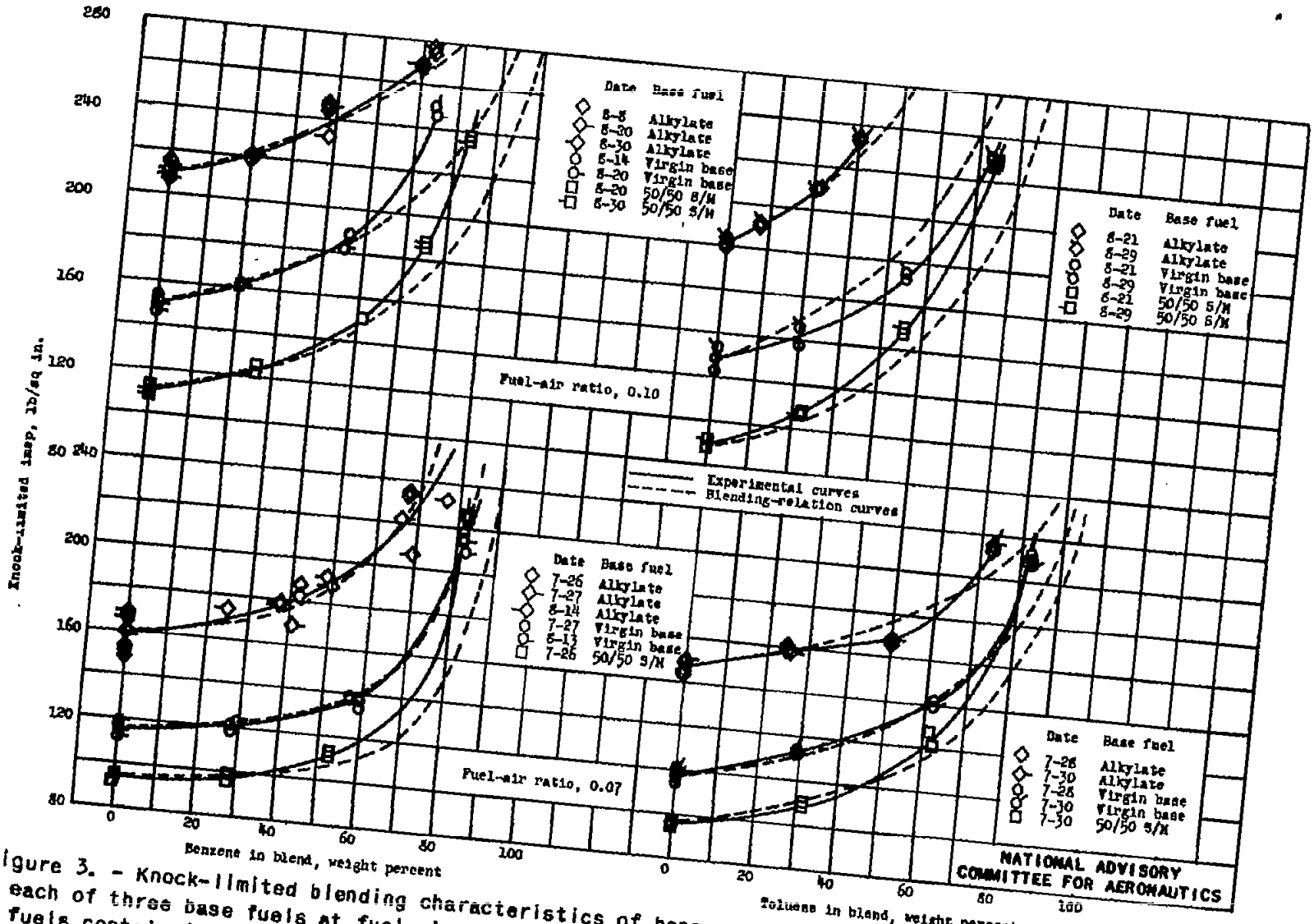

Figure 3. - Knock-limited blending characteristics of benzene and toluene individually blended with each of three base fuels at fuel-air ratios of 0.07 and 0.10 in an aircraft-engine cylinder. All fuels contain 4 ml TEL per gallon. Dashed curves show indicated mean effective pressures predicted by extended blending relation.

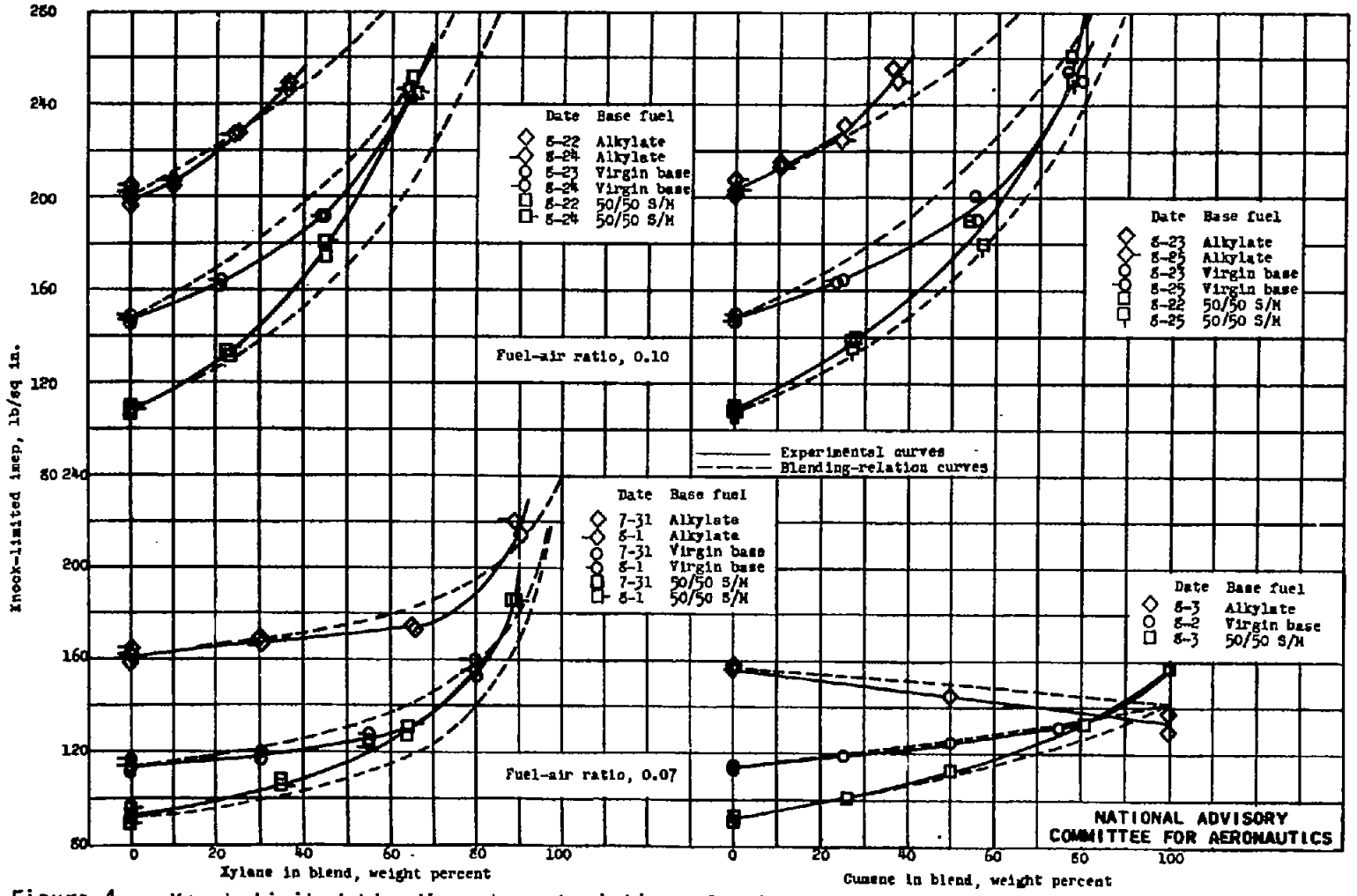

Figure 4. - Knock-limited blending characteristics of xylene and cumene individually blended with each of three base fuels at fuel-air ratios of 0.07 and 0.10 in an aircraft-engine cylinder. All fuels contain 4 ml TEL per gallon. Dashed curves show indicated mean effective pressures predicted by extended blending relation.

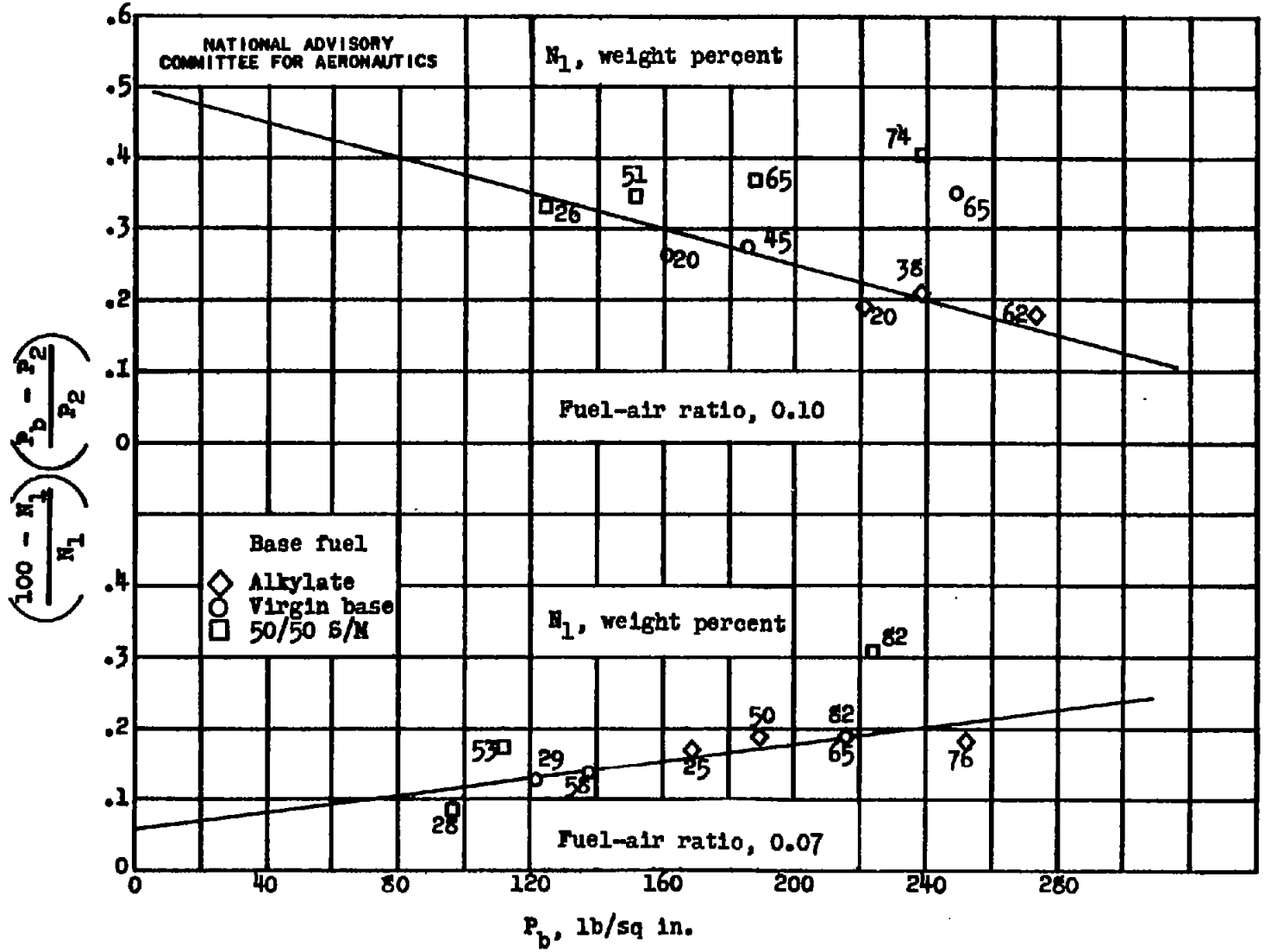

Figure 5. - Examples of straight-line plots used in testing extended blending relation for aromatics. Data points from faired curves in figure 3 for benzene.

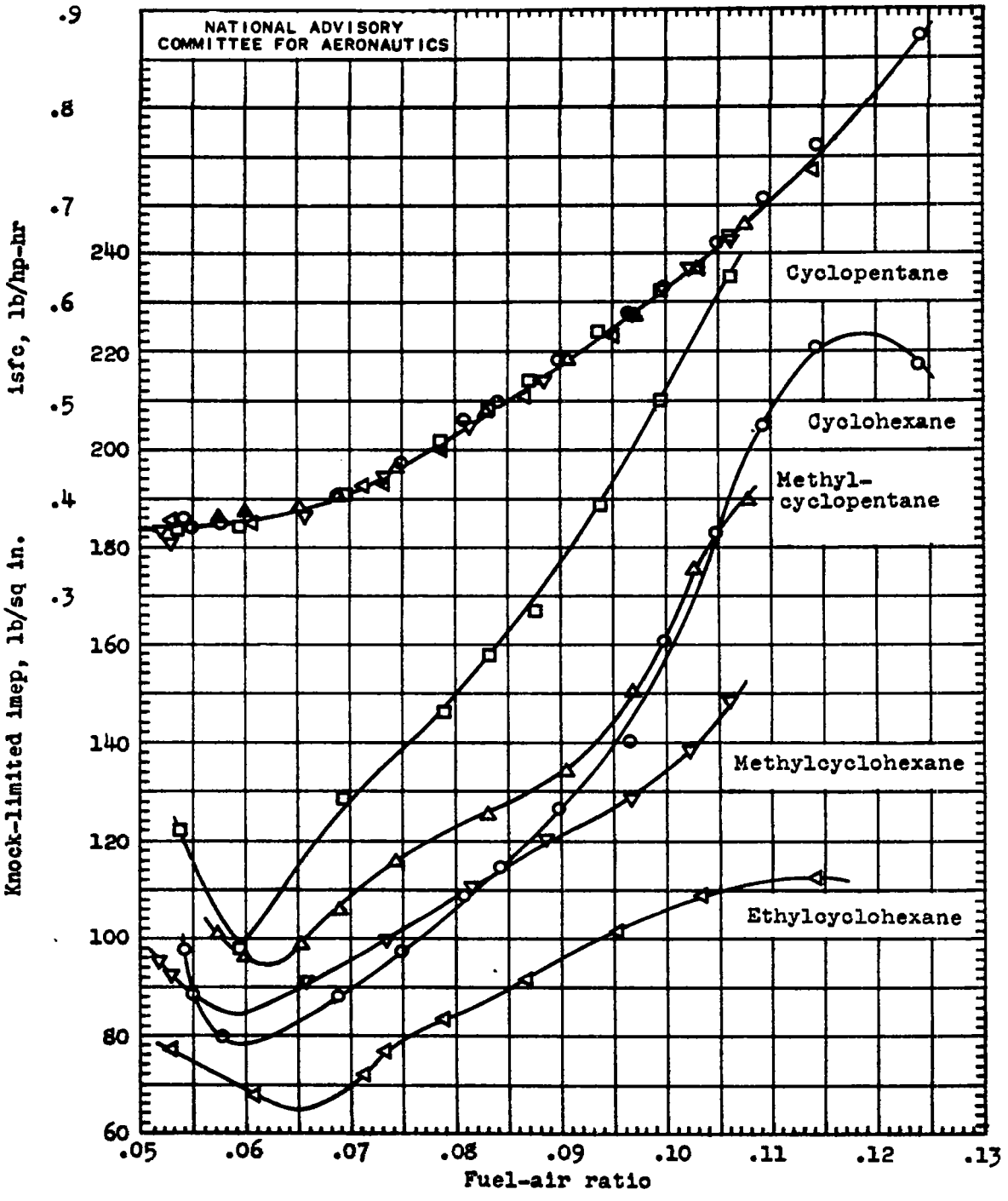

Figure 6. - Knock-limited mixture response of cycloparaffins in an aircraft-engine cylinder. All fuels contain 4 ml TEL per gallon.

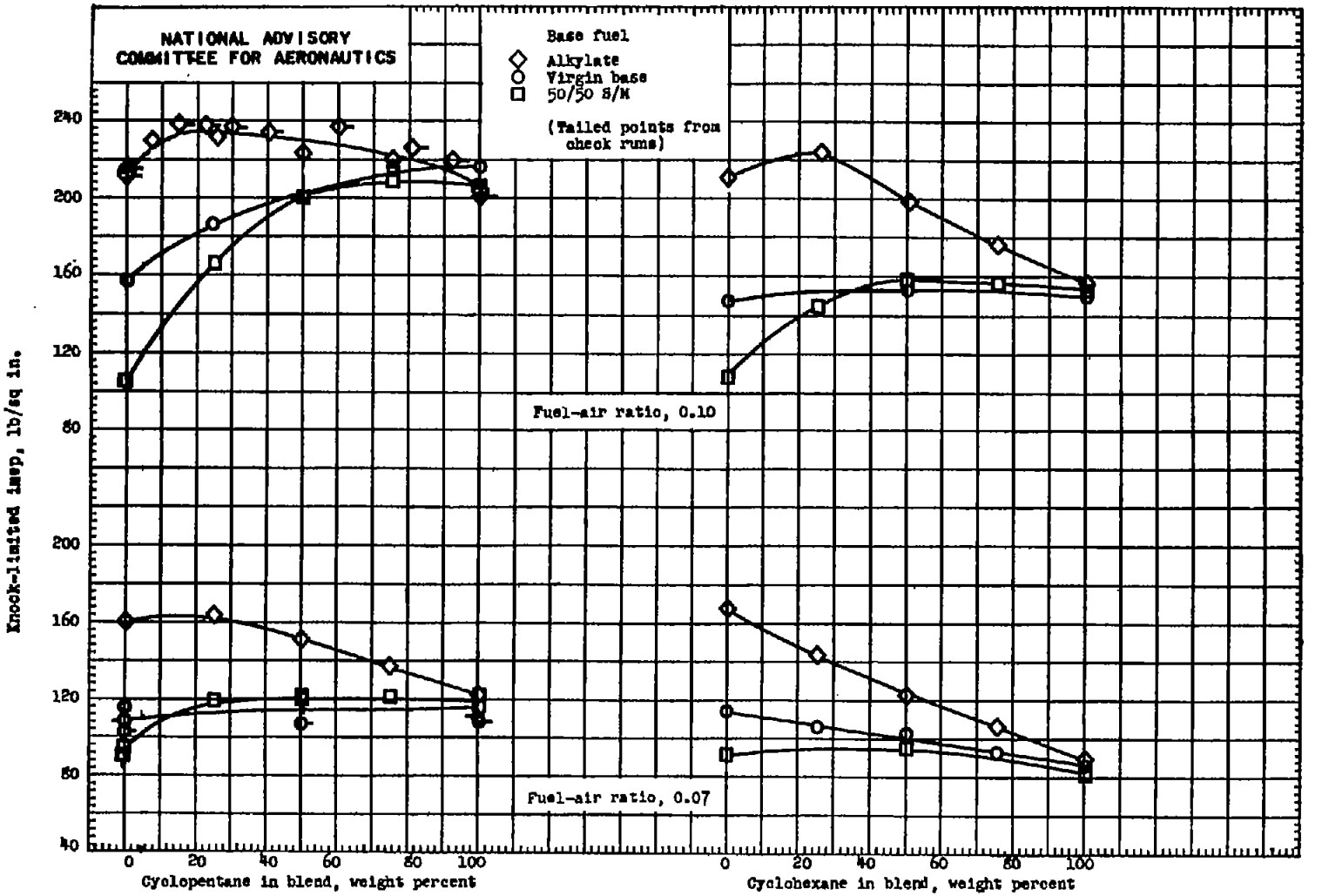

Figure 7. - Knock-limited blending characteristics of cyclopentane and cyclohexane individually blended with each of three base fuels at fuel-air ratios of 0.07 and 0.10 in an aircraft-engine cylinder. All fuels contain 4 ml TEL per gallon.

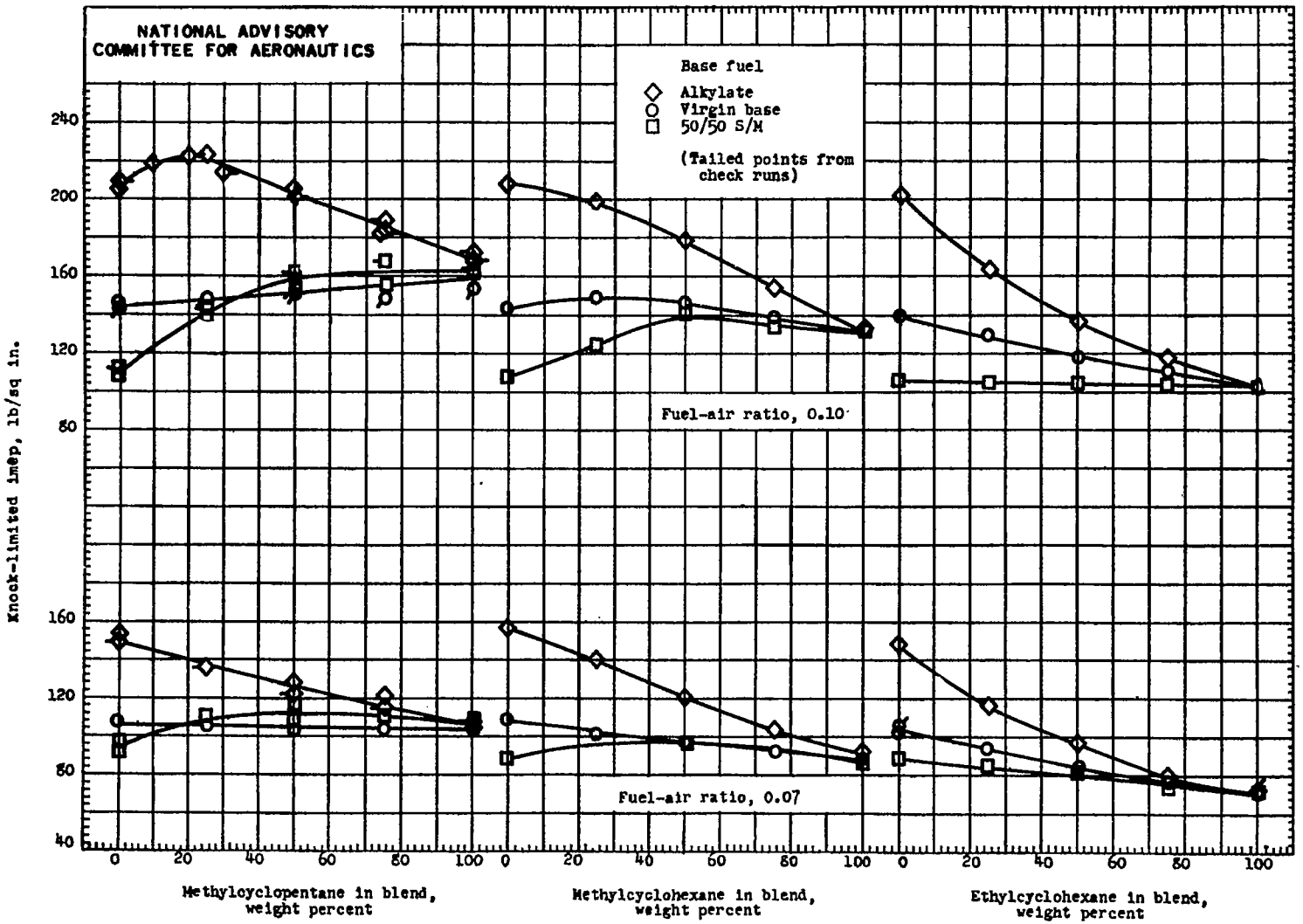

Figure 8. - Knock-limited blending characteristics of methylcyclopentane, methylcyclohexane, and ethylcyclohexane individually blended with each of three base fuels at fuel-air ratios of 0.07 and 0.10 in an aircraft-engine cylinder. All fuels contain 4 ml TEL per gallon.